

Development of Ballistic Needle-Punched Felts

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AS A RESULT of the proven effectiveness of body armor in reducing combat troop casualties, the Army has supported research and development programs which have as their goal the improvement of ballistic materials for personnel armor. The current Army standard fragmentation vest is an all-textile material, the basic ballistic-resisting component of which is composed of 12 layers of basket weave 14 oz/sq yd nylon duck weighing approximately 8½ lb per medium sized vest. The weight of this item clearly needs to be reduced without sacrifice of protection.

As early as 1956, nonwoven needle-punched felts were shown to offer significant ballistic protection while at the same time showing promise for significant weight savings when compared to woven fabrics. The first military specification prepared in 1967 was for a felt which sacrificed about 20% in ballistic resistance but was one-third the weight of the standard fabric assembly. High areal density felts lose their advantage over standard fabric. Thus, at 19 oz/sq ft, which is the areal density of the standard fabric assembly, the ballistic protection of felt and fabric is essentially the same. At low areal densities attained by using multiple layers of low density felt, it is possible to prepare felts at half the weight while retaining 92% of the ballistic protection offered by the standard woven fabric vest.

The mechanisms by means of which needle-punched felts defeat or react to a given ballistic missile are unknown to a large degree. It is clear, however, that the mechanism is different from those operating with other materials such as woven fabrics, metals, ceramics and plastics. The mechanism of felt deformation appears to be highly dependent upon fiber-fiber friction described as a "slip-stick" mechanism.

The ultimate level of ballistic protection theoretically, or even practically, attainable has been difficult to ascertain. A systematic and isolated variation of the important parameters affecting ballistic performance of needle-punched felts is not possible experimentally at the present time. However, the following review will list and discuss the more important fiber and fabrication parameters, the types of dynamic experiments which have been conducted to elucidate the felt deformation mechanism and the deficiencies which must be surmounted to make greater use of needle-punched felts. As one of the principal aims of this review, the authors hope to obtain valuable feed-back from readers in the fiber production and finishing industries which will eventually result in improved needle-punched felts.

Discussion

As stated in the introduction, this review includes three parts: (1) fiber and fabrication parameters; (2) dynamics

Abstract

The fiber and fabrication parameters and the dynamics of the impact of a felt with a missile have been reviewed for needle-punched felts. At low areal densities the ability of needle-punched felts to resist penetration by a fragment is superior to that offered by any other materials. On the other hand, as the allowable weight of protective material is increased to protect against fragments with higher velocities, other materials become competitive. The extent to which needle-punched felts maintain their superiority over other materials at moderate areal densities is very dependent upon certain fiber and fabrication properties. For fiber properties, the use of the highest tenacity polyamide fibers gives the best properties. In the case of fabrication, a relatively low degree of needling furnishes the best ballistic properties. In general, the thicker the felt that can be tolerated (for the same weight as areal density) the better the ballistic resistance. Additional work is required to determine the effect of fiber properties such as fiber denier, fiber surface treatment, molecular weight, molecular weight distribution, and elongation upon the ballistic properties of the resulting felts. This work, in turn, depends upon the availability of model fibers by which these parameters can be studied independently.

of felt upon impact, and (3) felt deficiencies.

Finally, the reader would hope for a standard test method, ballistic or mechanical, which would allow one to rate the felt materials in a definitive manner. Factors such as missile shape, spin and size can affect variations in ballistic response for different materials. This is a field of active study in military laboratories but this information is not available for public dissemination at the present time. Most available information concerns tests with a .22 caliber 17 grain fragment simulator and the results of such tests will be used throughout this report as a measure of the effectiveness of various felts. The description of the .22 caliber missile and of the ballistic test is available in two military specifications, MIL-P-4659 and MIL-STD-662. Briefly, the term V50 refers to the fragment velocity for which statistically one would predict a 50% probability of penetration.

Fiber and Fabrication Parameters

Most of the information available in the literature in this area is concerned with natural felts, felts which have incorporated a binder, or felts which have been heavily needle-punched. The important variable parameters associated with the preparation of needle-punched synthetic felts especially as they might be related to ballistic resistance have not been reported. Some of the factors that

would appear to merit consideration are included in Table I.

One could point out obvious additions to this list such as modulus, crystallinity, fiber denier, draw ratio and work-to-break. However, the last two of these parameters are indirectly included in tenacity and elongation while the appropriate fibrous materials for determining the influence of the former three parameters have not been available heretofore. Some conclusions possible at the present time concerning these parameters are listed below.

Molecular Type. The use of polyamide type fibers results in the best needle-punched felts as measured by ballistic resistance to the 17 grain fragment simulator. This superiority was noted early in some tests by Laible and Supnik¹ but has been confirmed by more extensive studies by Ehlers² and Keith.³ Insufficient effort was expended in maximizing the efficiency of each fiber type so it is possible that the performance of some of the fibers could be upgraded until they become more nearly competitive with the polyamides. In specialized applications such as the preparation of felts which were buoyant as well as protective, the use of treated fine denier acrylic fibers has been advocated;⁴ however, it has been the experience of the authors that these buoyant vests were never found to be ballistically equivalent to the polyamide felts.

A second place listing in the ballistic resistance offered by different molecular types is given to polypropylene. This listing is somewhat confirmed by the use of a combination of polypropylene felt, foam and nylon fabric in a Navy flotation vest with ballistic protective qualities.⁵

Molecular Weight. The higher the molecular weight of a polyamide-type fiber the better the mechanical properties that can be realized in the fiber. The better the mechanical properties of the fiber in a needle-punched felt, the better the ballistic resistance achieved. Here the user of the fibers is very dependent upon the fiber producer and the fiber producer is dependent upon his polymer chemists and rheologists not only to attain the high molecular weights in the polymer but to be able to process these high molecular weight polymers into fibers. The use of acid terminators has been very useful in this regard resulting in lower viscosity with higher number average molecular weight.

Tenacity. The higher the tenacity of a fiber (all other factors being equal) the better the ballistic performance of the resulting felt.⁶ Tenacity, the textile scientist's term for the strength of a fiber or yarn-related to its linear density, turns out to be an especially convenient expression for the field of ballistic protection. This is because of the paramount importance of obtaining the greatest protection for the smallest weight of protective gear. As is well known, this parameter of tenacity is closely related to the molecular weight previously discussed.

Molecular Weight Distribution. The molecular weight distribution should be as narrow as possible to combine high number average molecular weight with ease of processability.

Elongation. The low elongation fibers such as glass,

Table I
Fiber and Fabrication Parameters

A. Fiber	B. Fabrication
1. Molecular Type	1. Type of Needling
2. Molecular Weight	2. Density of Needling
3. Tenacity	3. Angle of Needling
4. Molecular Weight Distribution	4. Length of Fibers
5. Elongation	5. Thickness of Felt or Density of Felt
6. Fiber Surface	6. Angle of Ply

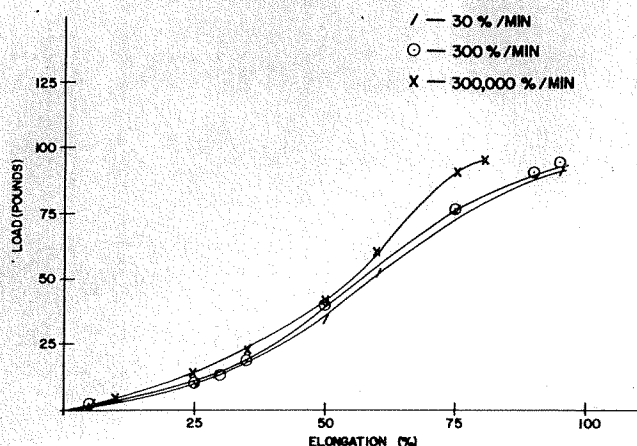


Fig. 1. Stress-strain curves for nylon felt.

stainless steel or even polyvinyl alcohol have not been useful for preparing needle-punched felts with a high degree of ballistic resistance. On the other hand, it should be pointed out that felts deform by a different mechanism than fabrics even if prepared from the same type of fibers. The stress-strain curves for nylon felt in Fig. 1 show that although the nylon fibers have an elongation to break of 20%, the resulting needle-punched felt has a much higher elongation of 90-100%. Thus, the translation of such fiber properties as elongation or even tenacity to felt properties may be hazardous.

Fiber Surface. The mechanical testing of felts and yarns has indicated that needle-punched felts deform by a frictional "stick-slip" mechanism. As a minimum, the interaction between the individual fibers play a predominant role in determining the mechanical properties of needle-punched felts. One could logically hope to improve the performance of a felt by using a simple lubricant (silicone) or abrasive (colloidal silica) to adjust the friction to the optimum degree. One also could consider the application of a polymeric treatment to absorb the greatest quantity of energy possible during the impact. The absorption of energy during a ballistic impact is much more dependent upon response time than are the usual energy absorbing demands posed by most commercial uses of materials. Many studies could be cited to show that none of the treatments selected raised the ballistic properties of the resulting felts. Some typical results of such treatments are shown in Table II and Table III.

In summary, it can be stated that treatments utilizing polymers with low, intermediate, and high molecular weights and/or glass transition points have not improved the properties of felts. Future work in this area of surface studies will probably include grafting studies to modify the actual fiber surface. The Scanning Electron Microscope will be used to observe surface changes due to treatments and/or ballistic impact. Scanning Electron Micrographs of the polyamide fiber surface in the original condition (Fig. 2) and as altered by ballistic impact (Fig. 3) are

Table II
Influence of Polymeric Treatment upon
Ballistic Resistance of the Standard Felt
(54 oz/sq yd 1/3 in. thick Nylon Felt)

Copolymer	Add-On	V ₅₀
50-50 2-ethylhexyl acrylate and butylmethacrylate	5%	800 ft/sec
50-50 2-ethylhexyl acrylate and butylmethacrylate	2.5%	884 ft/sec
30-70 2-ethylhexyl acrylate and butylmethacrylate	5%	900 ft/sec
30-70 2-ethylhexyl acrylate and butylmethacrylate	2.5%	914 ft/sec
Control—No Add-On	0%	1059 ft/sec

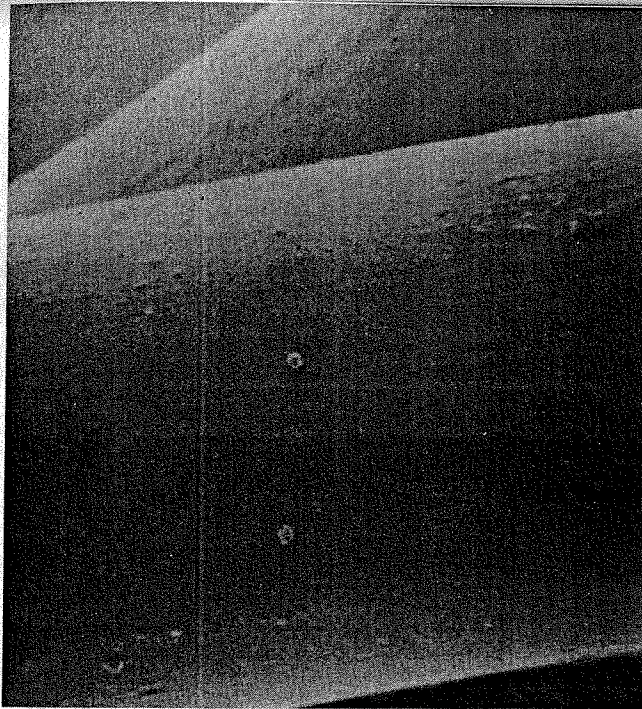


Fig. 2. SEM photograph of nylon fibers from needle-punched felt prior to ballistic impact (4114X).

shown which were obtained under a purchase order with Georgia Technological Institute.

Space limitations will not allow an item by item discussion of the remaining parameters important to the felt ballistic properties. However, from the listing of fabrication parameters only the density or total amount of needling has proven to be of significance. In general, the amount of needling must be kept low to allow the fiber-fiber interaction which is important to good ballistic performance. Excessive needling invariably lowers the ballistic resistance. The length of the staple fiber used for the preparation of the felt is only significant up to 3 in. in length. The performance ballistically arises with length to this point while fibers greater than this length tend to produce fabrication difficulties. The other parameters such as angle of needling or angle of ply appear to be unimportant in the over-all picture.

Dynamic Experiments

The initial experiment conducted with needle-punched felts was the simple stress-strain curve at different rates of testing. The resulting stress-strain curves (Fig. 1) showed that the felt deformation was several times greater than that of the individual fibers and that the shape of the stress-strain curve changed very little with a change of three decades in rate of straining. This lack of strain rate behavior is unusual for a viscoelastic material and demon-

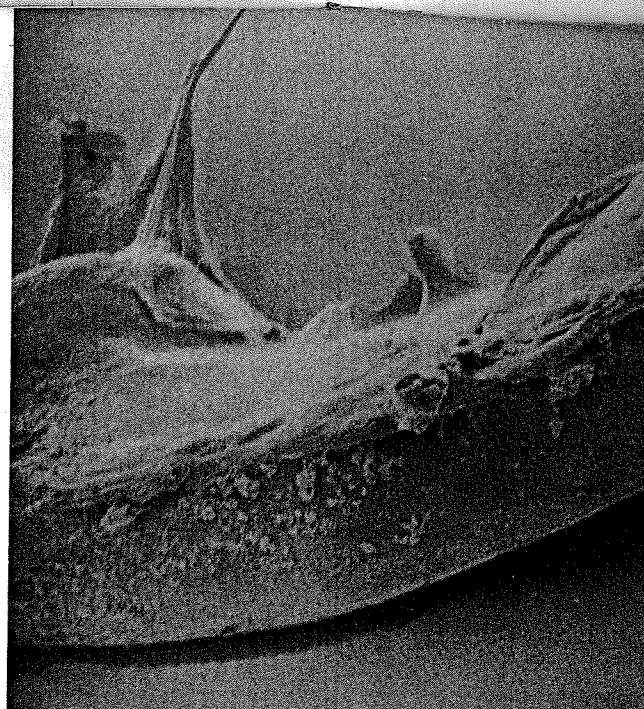


Fig. 3. SEM photograph of nylon fibers damaged in ballistic impact (2100X).

strates that the mechanism of deformation is much different from a simple stretching of the fibers to failure.

The next series of experiments were conducted by actually impacting a thin layer of felt with the 17 grain fragment simulator. Pictures were then taken of the resulting silhouette with a high speed motion picture camera (Dynafax). The type of pictures that result are shown in Fig. 4. These photographs are of the same missile impact with a time separation of 77 microsec between frames. The Dynafax actually gives a greater frequency of framing than

Fig. 4. Sequence photographs of missile felt target interaction. *cont on page 4*

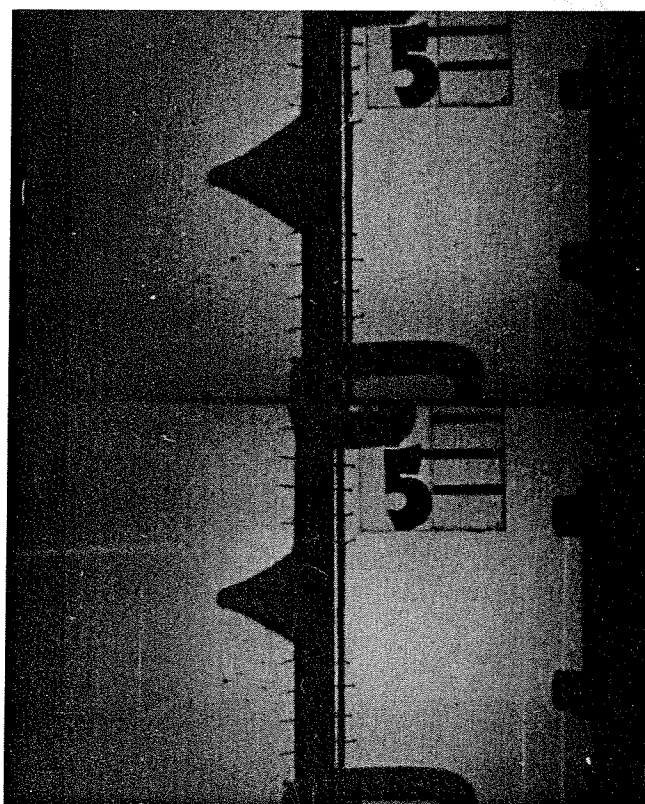


Table III
Ballistic Results on Felts Treated
With Dimethyl Silicone Fluids

Identification No.	Add-On	Viscosity of Silicone	M. W. of Silicone	V_{50} (ft/sec)
1	10%	50	5,000	864
2	10%	264	12,000	877
3	5%	1015	25,000	911
4	10%	1015	25,000	888
5	15%	1015	25,000	871
6	10%	10270	57,000	746
7	10%	28600	80,000	779
8	10%	100000	100,000	
9	10%	1058000	150,000	811
Control	0%			980

this with a time between of 38.5 microsec but the alternate frames occur on the opposite strip of film not shown. In these pictures the missile moves from the left to the right in the horizontal direction with the result that the cone peak moves further and further to the right in subsequent frames. Measurements can be made of this progression and the position of the missile plotted as a function of time. Such a curve is shown in Fig. 5. Graphical differentiation can lead to curves of projectile velocity versus time (Fig. 6) and deceleration versus time. This latter curve has been shown as force versus time by use of Newton's Second Law in Fig. 7. This type of valuable information suffers from the disadvantage attendant to double differentiation (error magnification). A second measurement that can be made from Fig. 4 is the apparent radial enlargement of the cone. Measurements in the vertical direction give such information which with only one graphical differentiation results in figures for the velocity with which the target material reacts to defeat the missile. The simplest conclusion that can be drawn is that the felt reacts rather slowly to the missile with so-called kink velocities (vertical movement in Fig. 4) of 200-250 ft/sec as contrasted with velocities double that figure for nylon fabric. This result explains the reason why felt tends to lose its advantage over fabric and other materials at the high areal densities where the objective is to defeat higher velocity missiles. The large extension of the felt in the horizontal direction in Fig. 4 explains why felts have an advantage at the lower areal densities.

Felt Deficiencies

The ballistic performance of felt at 6-7 oz/sq ft is at least equivalent to double or triple that weight of fabric. For this reason one would predict that felt would supersede fabric or any other material at low areal densities. The following deficiencies prevent the widespread use of felt for personnel armor.

High Bulk. The thickness of the felt (.5 in.) required to attain the same ballistic protection as nylon fabric is several times that of the heavier weight of fabric. This produces some problems in tailoring and perhaps in comfort.

High Water Absorption. The needle-punched felt can absorb up to six times its weight in water. Water repellent treatments are only partially effective and it is necessary to enclose the felt in a plastic envelope. A subsequent break in the envelope causes a catastrophic moisture pickup so that extremely durable plastics are required.

Velocity Limitations. The advantage of felt for ballistic protection at present extends only up to 1300-1400 ft/sec. For higher velocity missiles characteristic of small arms fire, other types of materials must be used.

Conclusions

This brief review shows that the ballistic performance of needle-punched felts is improved by the use of high tenacity polyamide fibers, a low density of needling, a moderate staple length of 3-4 in. and by the maximum allowable thickness. Finishes ranging from lubricants and polymeric materials with glass transitions from -100°C to 100°C to abrasives like colloidal silica did not have any beneficial influence on the ballistic performance. This result along with the need for a low density of needling and the poor ballistic performance of bonded felts illustrates the importance of freedom for fiber-to-fiber interaction and movement for optimum ballistic performance. It is unlikely that the fibers as received possess exactly the proper degree of lubricity or friction and some type of fiber finish should improve the felt's performance. The finish might have to be grafted to alter the individual fiber surfaces to the proper degree.

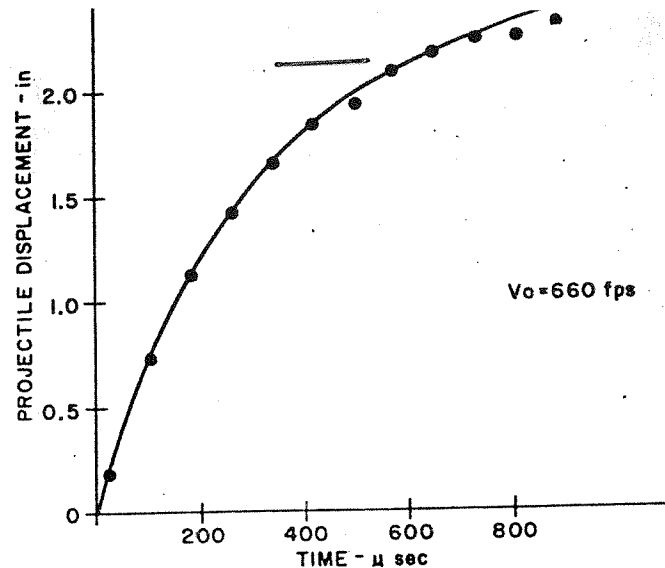


Fig. 5. Projectile displacement versus time curve.

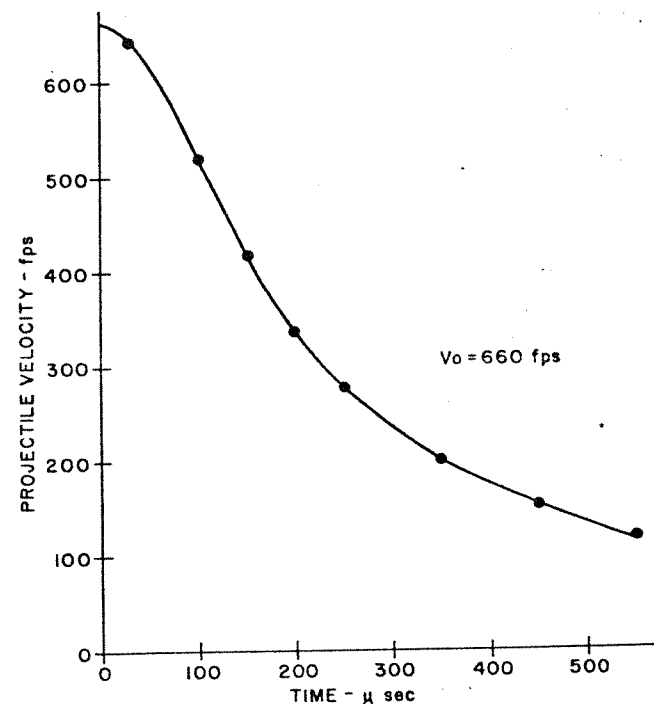


Fig. 6. Projectile velocity vs. time curve (Felt No. III).

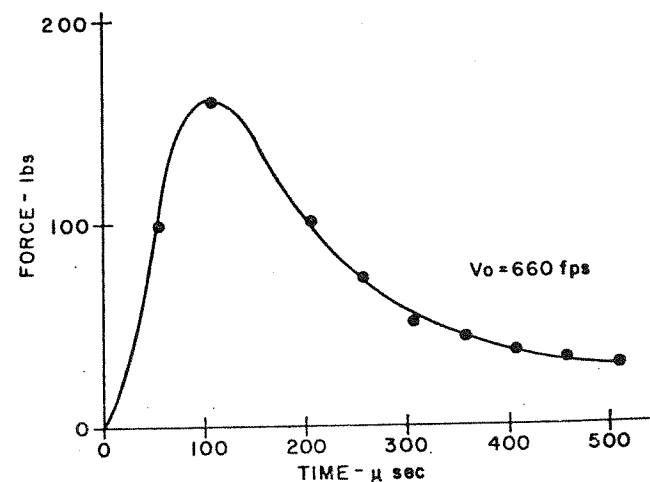


Fig. 7. Force versus time curve.

Factors such as the exact influence of fiber denier, fiber crystallinity and fiber elongation upon the ballistic resistance of the resulting needle-punched felts have not been isolated because of the absence of comparable textile fibers. Work is currently in progress to obtain and test such materials but in general it is difficult for the fiber producer to furnish fibers in which a single variable (denier, elongation, etc.) is varied. □ □ □

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